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The Object Display: Principles and a Review of Experimental Findings

Christopher D. Wickens
University of Illinois

for

Contracting Officer's Representative
Michael Drillings

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Michael Kaplan, Director

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This report summarizes and integrates the results of several experiments that have been conducted during the contract period comparing object displays of multidimensional information with more conventional bargraph displays. The context in which this summary is presented is a theory of information integration which proposes that the benefits of object displays will be enhanced to the extent that information from multiple channels must be integrated, and will be diminished to the extent that separate channels must either be processed independently, or information in certain channels must be filtered out. The experiments described involve rectangular, triangular, pentagon and single point objects, conveying data in paradigms related to statistical data analysis, decision making, and process control. The results generally support the theory of an object-display benefit for integrated information; furthermore they indicate that the object display effects are independent of the degree of correlation between variables.

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THE OBJECT DISPLAY: PRINCIPLES AND A REVIEW OF EXPERIMENTAL FINDINGS

Christopher D. Wickens

1. THE OBJECT

The representation of several variables as dimensions of a single object is an issue with both applied and theoretical relevance. The applied issues relate directly to human factors efforts to better format the display of the multitude of information channels that are characteristic of a wide range of modern systems. These systems include for example those in aviation, in process control, in command and control, or in intensive care units. Examples of object displays that have already been developed for operational use include the conventional attitude display indicator in aviation, or the octagon safety parameter information display introduced for nuclear power plant monitoring (Woods, Wise, & Hanes, 1981).

Before the theoretical importance and analysis of object displays are discussed, it is important to make some effort to define exactly what is meant by an object. Our definition here is somewhat fuzzy, acknowledging that there is no absolutely critical defining attribute to "objectness," but that some attributes are more critical than others. The most critical of these is the presence of contours--an object is that which is defined by closed contours. Yet we acknowledge some flexibility even in this attribute because a point and line are each considered objects, even though, in their mathematically pure sense, these are not defined by contours. Furthermore objects can be perceived as such, even if their contours are not entirely closed, as those contours may be "filled in" by top down perception.

A second important (but not defining) attribute is close proximity in space. A representation is more "object like" if its attributes are close (say, the state of Arkansas), than widely distributed (the country of Russia).

Two closely related features of objects are familiarity and correlation of attributes. In fact these "meta attributes" of the object concept are themselves correlated, because that which makes an object familiar is the repeated co-occurrence of its features or attributes (i.e., a correlation in the observer's experience). Yet we do not define these as critical features, for co-occurrence may very well be absent in some quite legitimate objects. For example a modern sculpture, whose shape and features we may never have experienced before can appear to be quite object-like.

2. OBJECT DISPLAY PERCEPTION

The focus of the present report is not on the perception of natural objects in the three dimensional world, nor even of the two dimensional representation of those natural objects, but rather on the perception of two dimensional geometric objects, whose separate dimensions are intended to represent some set of values, necessary to support task performance.

There are data from four somewhat different paradigms and theoretical approaches that bear upon the potential costs and benefits of object displays. These will be discussed in an order that corresponds to the complexity of their predictions, although this order does not necessarily correspond to the chronological order of research development.

Object Integrality. Kahneman and his colleagues (Kahneman & Treisman, 1984; Kahneman & Henik, 1981; Kahneman & Chajczyk, 1983) have argued that the integral properties of objects enable their attributes to be processed in parallel, in a relatively cost-free fashion. Kahneman has introduced the notion of a mental "object file," whereby perceptual activation of one attribute of the file automatically carries with it activation of other attributes. There is perceptual competition between object files, but not between attributes within a file. Impressive support for this view has been provided by experiments by Kahneman and Chajczyk (1983), Kahneman and Treisman (1984), Duncan (1984), and Lappin (1967). Kramer, Wickens, and Donchin (1985) have found that increases in the demand of processing one attribute of an object facilitates the processing of other attributes, a finding that is quite consistent with the assumption of a necessary coupling between the processing of object attributes. Note that the object integrality principle predicts an overall inherent benefit for object representation that is not assumed to be modified by the task characteristics (i.e., by the nature of the task to be performed using the object-represented information). Potential sources of this modification will be discussed below.

Emergent Features. While the object file approach specifies a general advantage to object integrality, resulting from the reduced resource demands of processing a single object, empirical work by Pomerantz (1981), identifies specific enhanced benefits to object configurations that are observed under certain circumstances. These are circumstances in which a particular set of features in the stimuli combine to form a new feature that directly serves the task at hand. Pomerantz (1981) has referred to this as an emergent feature. For example, two linear stimuli that are now connected as contours of a geometric object now produce an emergent feature--angle--that did not exist previously. While object integrality is not necessary to form emergent features, the latter are clearly encouraged by the greater proximity brought about by objectness.

Integral Dimensions. Emergent features are said to bring about a benefit for object integrality as a result of proximity. A corresponding proximity benefit has been introduced in Garner's theory of integral dimensions (Garner, 1970; 1974; Garner & Fefoldy, 1970). However, this theory extends the predictions of object effects derived above, because the theory also identifies the circumstances of a proximity cost. While the details of this theory, and the arguments of its recent critics (e.g., Cheng & Pachella, 1984) are too lengthy to treat here, its fundamental characteristic from the point of view of the current paper is Garner's specification of the interaction between a stimulus dimension--whether a pair of stimulus dimension are integral or separable--and a task dimension--whether a single one of independently varying dimensions are to be focussed upon, or whether both of a pair of redundant dimensions are to be processed. While Garner has not explicitly applied his theory to object integrality, it is apparent that the dimensions of a single object often meet Garner's criteria for integrality, while dimensions of two objects never do so.

Compatibility of Proximity. The research of Garner has specified both costs and benefits of the integrality typical of objectness, in terms of task characteristics. Wickens and his colleagues more recently have expanded both the stimulus characteristics of integrality and the definition of task processing characteristics in a way that incorporates some more specific predictions regarding the circumstances of both costs and benefits to object integrality (Wickens et al., 1985; Carswell & Wickens, 1986, in press; Casey & Wickens, 1986; Boles & Wickens, 1983; Barnett & Wickens, 1986; Goettl, Kramer & Wickens, 1986). According to the "compatibility of proximity hypothesis," the similarity among any two (or more) stimulus dimensions can be defined in terms of a multidimensional space of such attributes. These include not only features such as spatial proximity or adjacency, that are important definers of objects but also other characteristics such as shared color, size, brightness or input modality. Proximity of input dimensions will benefit any task that also requires proximity of central processing--that is, some form of mental integration (comparison, addition, multiplication) of those input values. However, proximity will harm performance of any task that either requires focussed attention on one of the attributes, or divided attention between the attributes (i.e., independent processing). These relations are shown in Figure 1.

The experimental results collected in the three theoretical areas discussed above may be placed within this broader framework. For example, the work supporting the object file concept has typically employed divided attention tasks, requiring judgments on multiple attributes of a stimulus (e.g., Lappin, 1967; Kahneman & Henik, 1981). Pomerantz's work on emergent features has examined both divided and focussed attention. Garner's work has examined focussed attention as the primary task characteristic in which a cost to integrality was observed. Whether the tasks in which Garner's integral dimensions produce a benefit, involve focussed attention or integration however cannot be readily determined because, given the complete redundancy of stimulus values along two dimensions, typical of this paradigm, it cannot be established if the subject is responding to both dimensions (integration), or one or the other (focussed attention).

The purpose of the current report is to review and integrate the work that has been sponsored by the Army Research Institute in our laboratory, which has examined the interaction between task type (integration versus independent/focussed attention) and display proximity, when the latter dimension has been defined explicitly in terms of object integrality. Such a review however would be scientifically incomplete unless it included a reference to other relevant work in our laboratory. In this regard two additional projects will also be discussed: Carswell and Wickens (1986, in press), and Goettl, Kramer, and Wickens (1986). Additional details of ARI-relevant work may be found in the associated technical reports.

3. FRAMEWORK FOR EXPERIMENTAL COMPARISON

On the following pages, seven different paradigms will be described. Each paradigm is defined by a pair of "close" and "distant" displays that are contrasted. Within each paradigm, there may be more than a single experiment, and/or a single condition, with these conditions contrasting different degrees of processing integrality (i.e., integration versus independent processing or integration versus focussed attention). The conditions that are compared within an experiment may or may not have the same underlying scenario presented to the subject. The experiments then may be characterized by a number of different attributes as shown in the overview presented in Table 1. One of these is whether integration is compared with focussed attention/independent processing, integration, or both. Furthermore, it is recognized that the distinction between integration and focussed/independent processing is a continuum rather than a dichotomy. Many tasks require focussing on a subset of a larger number of dimensions, but integrating across that subset.

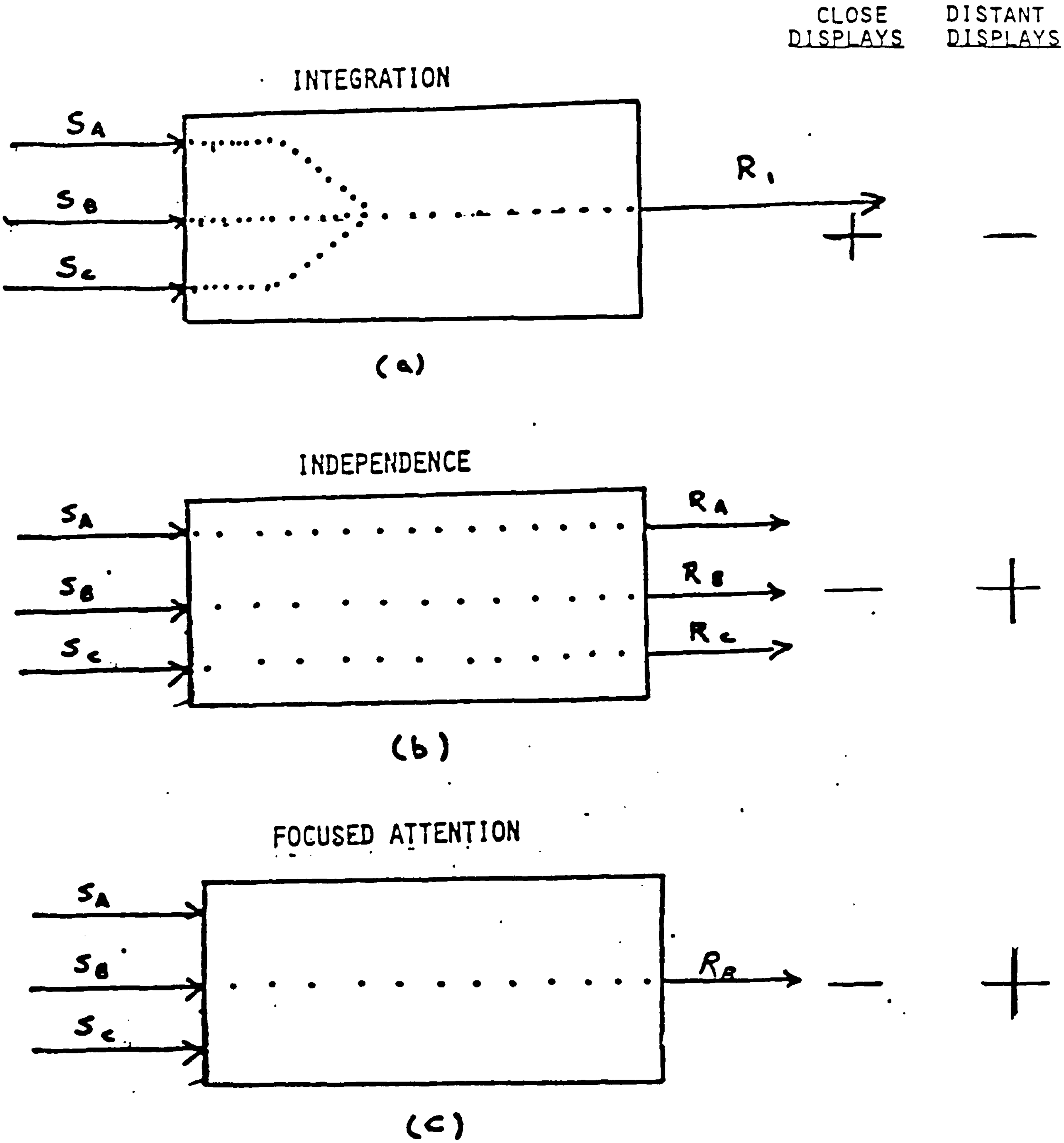


Figure 1. Relation between the benefits of proximate display formatting, and the nature of task information processing characteristics. Top: integration. Middle: independent processing or divided attention. Bottom: Focussed attention.

TABLE 1

			Central Processing			
			Integration		Attention	
Experiment	Object	Task Scenario	Pure	Partial	Focussed	Divided
1. Barnett & Wickens	2D	Decision Making	+		o	
2. Goettl, Kramer & Wickens	2D	Statistical Inference	+			
3. Goettl, Kramer & Wickens	3D	Decision Making (Judgment)	o		-	
4. Carswell & Wickens	3D	Process Control	+		-	-
5. Casey & Wickens	5D	Process Control (r)*	o	-		
6. Casey & Wickens	5D-3D	Process Control	-	-		
7. Jones & Wickens	5D	Process Control (r)*	+			

*(r) indicates a manipulation of correlation.

A second attribute of Table 1 concerns the scenario within which the tasks are embedded. These have involved either a process control environment, a multicue decision making environment, or one of statistical data interpretation. All of these environments well characterize the integration requirement. A third characteristic of the table concerns the number of attributes that must be integrated. When object displays are contrasted, this number naturally defines the shape of the geometric object, whether point plots or rectangles (2D), triangles (3D), quadrangles (4D), pentagons (5D), octagons (8D) or 9 dimensional shapes. While Woods, Wise, and Hanes (1981), and Jacob, Egeth, and Bevon (1976) have examined the last two displays respectively, our experiments have only focussed on displays of 2, 3, and 5 dimensions. A fourth attribute characterizing Table 1, concerns whether or not the experiment manipulated the correlation between variables. The reason that this manipulation was included, and seemed to be of potential importance, was our initial hypothesis that correlation might enhance object display benefits. Two lines of reasoning underlie this hypothesis: (1) Garner's research had found that integral displays facilitated classification when there was complete redundancy (r = 1.0) between two dimensional levels. (2) From an ecological perspective, as we experience objects in the natural world, the dimensions of a single object are more likely to be correlated than the dimensions of two separate objects. Hence a case can be made that "objectness" and "correlation" go together in real life.

The final attribute of the table refers to the conclusions drawn. These are coded, qualitatively, by a +, o, or - that indicate the direction of an "object display advantage" in the condition listed. That is, the performance in the object configuration relative to the separated condition. A "+" indicates object superiority, a "-" indicates inferiority, and a "o" of course indicates no difference.

Across all of the experiments, the separate-display condition against which the object was compared, was a set of n bargraphs. In each experiment, the displays were carefully configured to ensure that the visual lobe surrounded by both displays was approximately equivalent, as was the range and velocity of display motion. Hence we believe that any findings of differences that we observe are based upon differences in the perceptual-cognitive interface, and not upon peripheral sensory characteristics of the visual system.

4. EXPERIMENTAL FINDINGS

(1) 2-D Displays: Multicue Decision Making

The physical world is characterized by a number of important multiplicative relations. These include such relations as volume = pressure x temperature; distance (or amount) equals rate x time; or voltage = current x resistance. Such relations are important because both the product, and the two terms that combine multiplicatively to make that product, are important. Hence, the monitor of such displays may wish to have equal access to the product and the terms. An important multiplicative relation also exists in the informational world of decision support, in which the total worth of an information cue is equal to the product of its diagnosticity in chosing between competing hypotheses, and its reliability (Johnson et al., 1973; Schum, 1975).

The present experiment examined performance in a multicue inference task, in which the reliability and diagnosticity of cues were presented either as two adjacent bargraphs or as the height and width of a rectangle. In the context of the earlier discussion in this paper, the rectangle has been shown to meet some of Garner's criteria for integrality (Fefoldy, 1974). Furthermore the rectangle would appear to have a particular advantage in that its area is an emergent feature that directly corresponds to the desired product of information worth. To the extent that rectangle area is a commodity that is directly perceived (i.e., Weintraub, 1971; Anderson & Weis, 1971), then the perceived emergent feature of area directly supports the task at hand. At least two recent studies have explicitly capitalized on this multiplicative characteristic of rectangle area for object display representations (Cole, 1986; Scott & Wickens, 1983).

In the present experiment (Barnett & Wickens, 1986; Wickens, Goettl, Barnett, & Kramer, 1986) subjects were asked to observe the display of a series of hypothetical 2-dimensional cues bearing on the likelihood of success of an airborne mission. Each cue varied in its reliability and diagnosticity. Following presentation of the series, subjects were asked to make an integrated confidence estimate of the likelihood of success. Different groups of subjects saw the two attributes of each cue represented as either a pair of bargraphs or as a rectangle, defined by its height (reliability) and width (diagnosticity).

The results indicated a significant advantage for the rectangle display in this information integration task ($F_{1,21} = 4.32$; $p < 0.05$). In order to examine the effect of display type on information focussing, each subject was periodically (and unexpectantly) probed to recall the value of one particular attribute (e.g., what was the diagnosticity of your most recent cue regarding headwinds). Thus, the interest was focussed on how well the displays had fostered a separate memorial representation of the attributes. The data indicated that in this focussed attention task, the object display advantage evaporated. There was now no difference between the two display formats in this "focussing" task. Hence, in Table 1, the study generates a "+" and a "o" in the integration and focussing column respectively.

(2) <u>2-D Displays: Graphical Data Interpretation</u>

Graphical data analysis and interpretation often require the processing of bivariate data; that is, a single data point, or "conceptual object," defined and represented by analog values on two different dimensions. A common example is provided by the measures of speed and accuracy in performance of a given experimental condition. The condition is the conceptual "object," while its speed and accuracy are the attributes. Such data are often represented by separate graphics, with separate axes. But if the <u>relation</u> between the two attributes needs to be understood, in order to appreciate, for example, the existance and magnitude of speed-accuracy tradeoffs, then the principle of compatibility of proximity should predict that understanding will be better when the two attributes are expressed as X and Y dimensions of a point plot (an object display) characterizing the typical speed-accuracy tradeoff plot (e.g., Pachella, 1974; Wickelgren, 1977).

In order to test this hypothesis, 40 subjects, all students in or graduates from Psychology statistics courses, were presented slides of a series of graphical data displays (Goettl, Kramer, & Wickens, 1986, Experiment 1). Each display depicted the speed and accuracy of two hypothetical conditions. Each condition in turn was labeled by a numeric value of some hypothetical treatment level (e.g., level "2" and level "4"). The subjects' task was to understand, at a glance, the combined effect on speed and accuracy of the two treatment levels. We tested this understanding immediately after the display was turned off, by presenting the subject with a third treatment level (e.g., level "8"). On a sheet of appropriately formatted graph paper the subjects were then to mark the speed and accuracy of the new data point, assuming a linear effect of the treatment in the two previous conditions. The accuracy of point placement on the two axes was assessed. Two data formats were contrasted; one in which a point plot of the 2D speed-accuracy space was used, and the other in which the two dimensions were represented as two adjacent bargraphs.

Both display formats were carefully constructed so that formal perceptual factors were equivalent (e.g., area of display lobe, dispersion of data), and the task was structured such that the response requirements were also equated for both formats (two horizontal lines drawn for the bargraph display; a horizontal and a vertical line drawn defining the intersection point for the point plot display). However, in spite of these controls, performance accuracy on both tasks was robustly better with the point plot object display ($F,1,20 = 71.47$, $p < 0.001$). Furthermore, more detailed analysis of the difference in error between the two plotted dimensions (speed and accuracy) revealed that the two were processed in parallel with the object display, but in series with the bargraph display. This experiment included no focussed attention control condition.

(3) <u>3-D Displays: Multicue Prediction</u>

The purpose of this experiment (Goettl, Kramer, & Wickens, 1986, Experiment 2) was to examine the object display in a different form of integration judgment--one related to multicue prediction. Such requirements typify the task confronting the decision maker who is required to evaluate two or more cues (for example, test scores for a student applicant), and infer their predictive relationship to a criterion (for example, success in the program of study). In the present study subjects viewed three cue values, depicted as ordinate heights on a graph. The three ordinates were either represented as 3 bargraphs, or as a triangle whose apices were formed by the 3 ordinate heights. The subjects' task in one phase of the experiment was to predict the criterion value of a function, generated by linearly combining the three values with different weights. After making their prediction on each trial, the subject received feedback regarding the actual criterion value. Previous research by Goldsmith & Schvanveldt (1984) had demonstrated a triangle display advantage in a similar experimental protocol.

During the second phase of the present experiment, the subject was again presented the same two display formats. However, in contrast to phase I, during the second phase one of the variables was irrelevant to the criterion (i.e., had a 0 weight in the equation). The subjects' task was to predict the criterion value based upon the identity of the two relevant variables. Therefore, unlike the first phase, this phase <u>did</u> require some degree of filtering or focussed attention.

Performance was scored on the basis of the product moment correlation between the true criterion value, and each subjects' response. The present results were consistent with the basic hypothesis in that the relative merits of the two displays was influenced, in the expected direction, by the degree of integration/focussing required of the task. In this experiment however, there was no overall object-display benefit, in contrast to Goldsmith and Schvaneveldt's findings. Instead, in phase I, requiring integration of all three variables, there was no reliable difference between the two display types. During phase II, when focussing was required (ignoring the irrelevant variable), a clear advantage for the separated display emerged. In other words an object display cost was induced by a focussed attention requirement. This finding is thus consistent with the proximity compatibility hypothesis.

A second experiment was conducted which employed the same general paradigm. however, a third display format was also included that represented a conceptual midpoint between the bargraphs and triangle display. In this condition the three variables were simply connected by a line graph. Two groups of subjects each performed judgment tasks using predictive formula s of different levels of complexity (additive, and multiplicative). A third group used an additive formula with correlated variables. The results failed to indicate any strong effects of display type. In fact, the only reliable effect was shown within the additive display, in which performance benefitted from the separated bargraph display, over the two more integrated displays. Thus, a comparison of the two additive displays, suggests that the presence of correlation between variables restores performance of the object display to a level that is equivalent to that of the separate display.

The possible conflict between the present results (showing no object display advantage for the integration task), and those of Goldsmith and Schvanveldt (1984), cannot be resolved on the basis of the current data, but may be related to different emergent features, resulting from the different ways of constructing the triangular object. In Goldsmith and Schvaneveldt's triangle, values were represented by radii emerging from the center. Therefore, large cue values on all variables produced a large triangle. In the present study, large cue values were presented less saliently, by a triangle higher in the graphical display. But the basal dimension of the triangle was always constant.

(4) 3-D Displays: Process Control

This set of three studies, described in greater detail elsewhere (Carswell & Wickens, 1986, in press), contrasts an object-triangle representation of three variables in a hypothetical energy process, with a 3-bargraph representation. In the first integration experiment, subjects monitored two systems, each with an output defined as either the sum or product of two time-varying inputs. The two inputs were either equally weighted or differentially weighted. The subject's task was to monitor the input-output relations of the two 3-variable systems in order to detect faults, or ramp changes in the relations. These changes produced gradual shifts or changes in the pattern of correlation between the 3 variables. The two displays representing the systems were either configured by sets of three bargraphs, or by an object-display triangle, whose height represented the system output and whose two basal legs, extending from a point directly below the vertical apex, represented the two inputs.

In the first experiment, across the various types of systems and system dynamics examined, detection performance was unambiguously superior with the object display, as assessed by either speed or accuracy. The second experiment replicated the first, using a slight variation on the nature of the failures. Again an object-display benefit was obtained. However, the experiment also incorporated a condition, like that in experiment 1 of the present report, designed to examine the effect of display format on attention focussing. While the subject was monitoring, the display would occasionally go blank, followed by a probe which called for the subject to respond with the remembered value of one of the six displayed indicators. This response was assumed to be accurate to the extent that the mental representation of the indicators' values remained distinct. While performance on the fault detection task again was superior with the object display, in a manner consistent with the compatibility of proximity hypothesis, the memory for the isolated attributes was better served by the separated bargraphs.

The third experiment examined the independent processing condition represented in Figure 1, using the two display formats. The six variables were now driven by six more rapidly changing, independent quasi-random functions. The subjects' task was to press one of six corresponding buttons each time one of the variables crossed a "zero point." Here again, in a manner consistent with the hypothesis, performance was best with the separated bargraph display.

(5) 5-D Display: Process Control

Slowly changing dynamic processes were also examined in the experiment described in detail in Casey and Wickens (1986; Casey, 1986). Subjects monitored a simulated heat distribution system, in which a central "furnace" provided heat to five satelite "chambers." As specified in the scenario, because of different local conditions in each chamber, each of these was also equipped with its own local heater. Therefore variations in temperature of the five was partly correlated (due to the action of the central heater), but was partly independent (due to the action of the local heaters). The subjects' task was to detect and diagnose blockages of the central heating supply to any of the five chambers. These blockages would cause the correlation of that heater's temperature changes with those of the other heaters to decline. Upon noticing some abnormality, the subject was to make a detection response to be followed by a diagnosis response, specifying which of the five chambers had failed. Three display formats were compared: a horizontal array of five bargraphs, an object-like pentagon, in which the five variables were represented by the distance of the apices from the imaginary center, and a "face" display.

The data of the face display are discussed in more detail in Casey and Wickens (1986). For the present purpose however, the relative merits of the bargraph and pentagon display appeared to depend upon the nature of the response required. When performance was examined in a speed-accuracy space, there was little difference between the two displays in terms of detection; but a clear superiority of the bargraph display in failure diagnosis.

Such results, initially puzzling, in fact were readily interpretable within the framework shown in Figure 1. Analyzing the tasks suggests that detection that something is wrong, requires holistic integration of all of the variables to detect a pattern of abnormality. Diagnosis of which chamber is blocked on the other hand, forces the subject to focus attention on only one variable (unlike the diagnosis task in Carswell & Wickens). That is, there was a 1-1 mapping between variable and diagnosis response. Hence the proximity compatibility hypothesis indeed predicts that the object display should fare relatively worse in diagnosis than in detection. These results are quite consistent also with the pattern obtained by Peterson, Banks, and Gertman (1981) in a comparison of object and separated displays for nuclear power plant monitoring. The reason however why the object display did not outperform the bargraph display in the detection task remains unclear. One possibility is that subjects actually performed the detection task by diagnosing the failure; although they were forced by the experimental procedure to indicate detection first, and then diagnosis, such detection may have been accomplished simultaneously with an attention focussing diagnosis strategy.

The experiment also included a manipulation of the overall level of correlation between the variables during their normal operations. A finding whose relevance will be considered below is that the level of correlation had no effect on the relative merits of the two displays.

(6) 3-D Display: Process Control

One major purpose of this study was to try to rectify the apparent contradiction in results between experiment 4 (Carswell & Wickens, in press) in which a triangle was found to be superior with an integration task that required the comparison of two variables, and experiment 5 (Casey & Wickens, 1986a), in which object superiority was no longer obtained for a pentagon, in a task which could be performed more by focussing on one variable. Accordingly, in the present experiment (Casey & Wickens, 1986b), two factors were varied orthogonally to bridge the differences between the two paradigms: (1) The nature of the system was either causal, with inputs producing outputs, as in Experiment 4, or correlational, with all variables having equivalent status during normal operation, as in Experiment 5. The causal system required a greater degree of integration. (2) Only 3 variables were displayed, but the 3-D object display was either a triangle, as in Experiment 4 with variables represented as vectors eminating from a central point, or a pentagon, as in Experiment 5 with two of the variables (the left and right "arms") frozen.

In addition to these variables, three other characteristics made the experiment somewhat more similar to Experiment 5 (pentagon) than Experiment 4 (triangle). (1) Failures involved discrete changes, rather than ramp changes. (2) The display was updated every 1/2 second, rather than semi continuously. (3) Subjects were required to give separate detection and diagnosis responses for a single system, rather than chosing which of two systems had failed. As in Experiment 5, correlational failures were imposed by decreasing the correlation of one variable with the others. Causal failures were imposed by creating a blockage of one input or the other, also leading to a change in the pattern of which variable correlated with which.

The detection and diagnosis latency and accuracy data in fact, reflected this similarity in procedures, producing a pattern that was more similar to Experiment 5 than to Experiment 4. Across most of these variables, for both the correlational and causal systems, there was an object display cost, one that did not vary extensively depending upon whether the system was correlational or causal, or whether the response was detection or diagnosis.

It is not entirely clear which of the factors that differed between the experiments produced the remaining discrepancy with the results of Carswell and Wickens experiment, which showed a substantial advantage for triangle displays (over bargraphs) with causal systems. One possibility pertains to the difference in configuration of the triangle display. In the present experiment, the variable magnitude was defined by the distance of apices from a central point, rather than by distances along the base and height. This change may have eliminated specific emergent features, which favored the triangle in Experiment 4. A second possible source of difference may be related to visual display load. Any advantages in reducing display load through object integrality would be considerably attenuated when there are but 3 variables (the present experiment) rather than 6 variables (Experiment 4). At present, whether these differences, or any of the other three differences between the two experiments described above, are responsible for the difference in results, cannot be firmly established.

(7) 5-D Display: Process Control

The previous process control tasks, described in experiment 4, 5, and 6 have all involved some level of integration, but also some degree of focussing, as failures were typically defined by some smaller subset of a larger number of variables. Hence at least some of the variables in all of these tasks could be considered as irrelevant to each particular judgment, and therefore were required to be selectively ignored. In the present experiment however (Jones & Wickens, 1986), the task required the subject to integrate all five variables, before a numeric judgment could be offered. The scenario was one of monitoring five temperature scales of a vat of chemicals, to form (and record) an estimate of the mean temperature of the process. As in experiment 5, the five readings were either represented as bargraphs or as a pentagon. In addition to the primary manipulation of display format, three further variables were manipulated with 2 levels each. Because of our interest in the potential effects of correlation, this variable was manipulated by two procedures: the degree of cross-correlation between the 5 variable was set at either 0 or 0.76, and the degree of autocorrelation within a variable was either 0 (random) or positive. In addition, the degree of homogeneity of the 5 indicators was varied. In implementing this latter manipulation, each indicator was said to have imperfect reliability. Hence in the heterogeneous case, the selected mean reading was to be the average of the 5 readings, weighted by their levels of reliability. In the homogeneous case, all variables were equally weighted. It was hypothesized that the greater similarity of the weightings in the homogeneous case, would produce a greater advantage for the homogeneous display.

The data were analyzed by a correlation analysis which correlated, over a series of readings, the optimal with the actual reading of temperature. In contrast to experiment 5, which also employed the pentagon display, the present results yielded a clear and consistent object display advantage ($F(1,23=27.40$; $p < 0.001$). This advantage was present across all conditions, but was apparently modulated by the correlation variables. The advantage was enhanced under that condition in which the variables were neither cross- nor auto correlated. That is, the object display advantage was greatest in the condition showing the greatest degree of randomness.

In addition to this finding, manifest as a 3-way interaction, there was a main effect of correlation--poorer performance with the uncorrelated variables--and an interaction of the two kinds of correlation: auto correlation within a variable had no effect on performance when there was correlation between variables, but when there was no such correlation, then auto correlation had a detrimental effect. The manipulation of weighting heterogeneity had no main effect nor interactions.

In summary, the most dramatic difference between this investigation, and that described in experiment 5, is the emergence of the object display advantage. Such reversal can in part be accounted for by the different degree of integration required in the two studies--relatively small in experiment 5, with a 1-1 mapping between variable, diagnostic state, and response, and total integration in the present study, with a many to one-mapping.

5. DISCUSSION

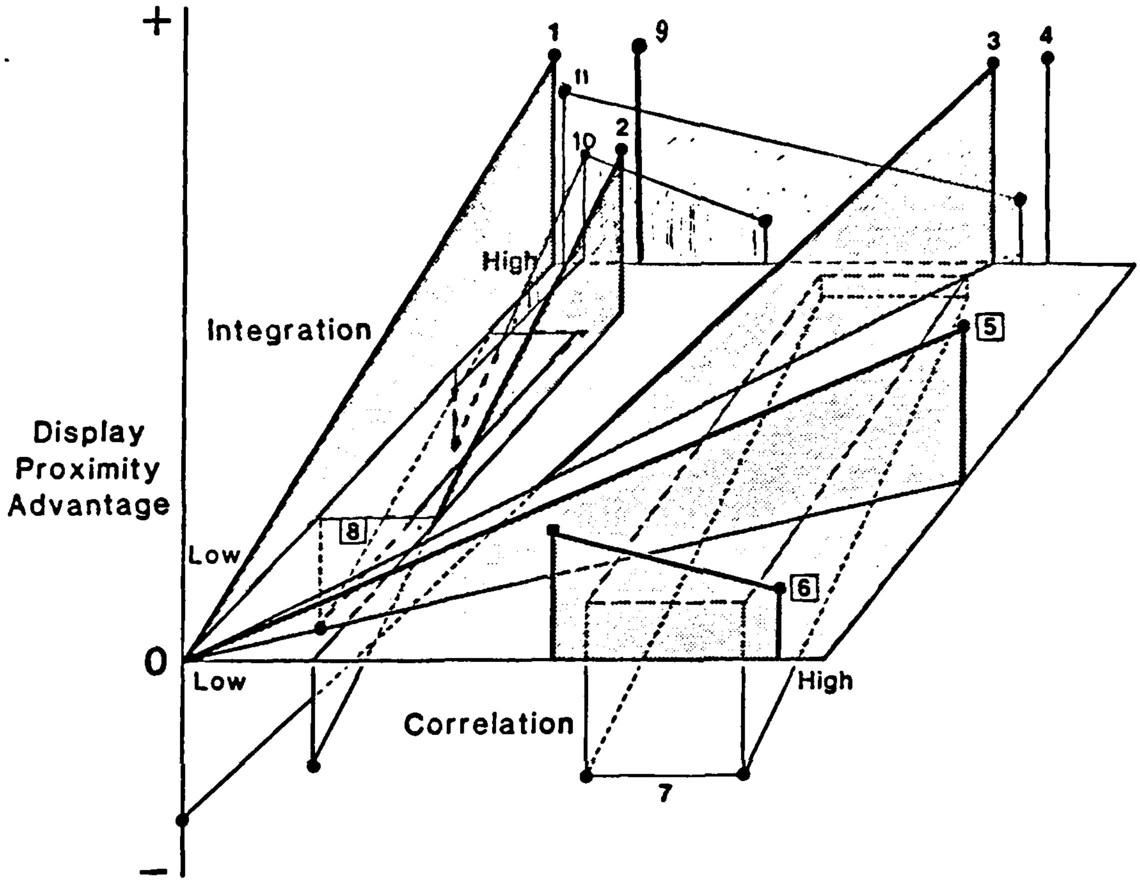
The previous treatment of experiments that have compared object representations with separate representations have all been carried out within our laboratories, most in the context of the present research contract. There are however other studies in the literature, that have compared object like displays with more separated representations, and whose description of experimental procedure allows some inferences to be drawn as to the degree of integration taking place. Figure 2, taken and expanded from Casey and Wickens (1986), includes a number of these experiments (Kramer, Wickens, & Donchin, 1985; Peterson, Banks, & Gertman, 1981; Garner, 1970; Goldsmith & Schvanveldt, 1984), along with the results described here, presented in a 3 dimensional space, which is defined by the degree of integration, the degree of correlation between variables, and the amount of display proximity advantage.

Thus each vertical line on the graph indicates a pair of conditions in which display proximity has been manipulated, by one form or another. A vertical "slice" is an experiment in which display proximity has been manipulated orthogonally with another variable that effects either the degree of correlation, or the amount of integration required. A vertical solid has manipulated both proximity and correlation orthogonally. For example, Casey and Wickens (1986) varied the degree of integration between detection (higher) and diagnosis (lower) using information sources which were always correlated, but whose correlation varied between conditions. Therefore this experiment is represented by a solid whose position on the plane is as labelled. Some experiments have contrasted the DPA in two conditions that have varied, in a confounded manner, both the correlation between inputs and in the amount of information integration required. Hence, the "planes" defined by the results of these experiments are oriented at an angle to the two axes.

The data represented in the figure do appear to reveal two consistent trends: (1) There is a general tendency for the DPA to increase (or a display proximity <u>disadvantage</u> to dissipate), as tasks require more information integration, or less divided and focussed attention. That is, the contours "slope" upward from the front of the figure to the back. This then supports the compatibility of proximity hypothesis presented in Figure 1. (2) The effect of correlation on the DPA appears to be substantially less. There is little trend in DPA from the left of the figure to the right as correlation between displayed variables increases.

In fact the most consistent trends across correlation, in those experiments in which the degree of correlation has been unconfounded from the degree of integration, seems to be a reduction in the DPA as correlation is increased (e.g., Jones & Wickens, 1986). It appears then that the affinity of integral dimensions for redundant information reported by Garner with simple 1 bit perceptual categorization tasks, may not generalize as an affinity of object configuration for correlated information in more complex information integration tasks. If anything, object displays appear to provide a greater benefit for the integration of less coherent (uncorrelated) information.

The representation in Figure 2 is clearly a "broad brush" global one, which tries to extract consistent trends across a number of different experiments with different paradigms, scenarios, time-constants, display formats and subject populations. Therefore, the degree of consistency in the figure, in spite of such variability in other factors, is a positive



1. Barnett & Wickens, 1986
2. Peterson et al., 1981
3. Carswell & Wickens, 1986, in press
4. Jacob et al., 1976
5. Garner, 1970
6. Kramer et al., 1985
7. Casey & Wickens, 1986a,b
8. Goettl, Kramer & Wickens, 1986 (Exp. 2)
9. Goettl, Kramer & Wickens, 1986 (Exp. 1)
10. Goldsmith & Schvanveldt, 1984
11. Jones & Wickens, 1986

Figure 2. This figure portrays the Display Proximity Advantage (DPA) as a function of the amount of correlation between the displayed values, and the degree to which those values must be integrated. Conditions for which integration is low are those that require either focussed attention on one source of information, or independent processing of several sources (i.e., dual or multi-task processing). Each experiment is designated by a number, identified in the legend above. Solid lines and planes indicate a Display Proximity Advantage, and thus lie above the plane of the surface. Dashed lines and open planes indicate experiments or conditions with a disadvantage to proximate displays. They thus depict negative values below the origin of this three-dimensional representation. The absolute height of lines is of less significance than the relative height of connected lines.

indication of the robustness of the phenomenon. It is this robustness that should make the compatibility proximity hypothesis a useful principle for human engineering design. One is not dealing with a small experimental effect that only emerge under tightly controlled laboratory conditions.

While the trend for an upward slope from front to back of Figure 2 is consistent, the fact that the absolute level of this trend, above or below the origin is variable, is less than fully satisfactory. As we noted for example, the investigations by Goettl, Kramer, and Wickens (1986. Experiment 3), and by Casey and Wickens (1986. Experiment 5) show only a diminution of a display proximity disadvantage, while Barnett and Wickens' (1986. Experiment 1) study shows an enhancement of a display proximity advantage.

This variability across studies may well be the result of different factors which might influence the DPA, whose effects have not yet been fully controlled. Two examples are the degree of motion, and the ratio of filtering to integration that characterizes those tasks which clearly contain both requirements. Another factor which remains less than perfectly controlled, is the degree and salience of emergent features. In fact it may well be that most variance in the extent of object display benefits can be attributable to the combined salience and relevance of the emergent features that support the particular task at hand. In contrast, it appears less likely that the cost of object displays for focussed or independent processing is due to characteristics of the emergent feature per se, rather than to the overall object-induced integration. Thus, in short, the overall trend represented from front to back of Figure 2, may in fact reflect two factors, which are often, but not manditorily coupled: emergent features, which are often present with object displays benefitting integration, and object-integration, which may bring about emergent features, but will normally disrupt focussed processing. The precise contribution of these two sources, and their degree of coupling or independence awaits further carefully controlled research on the focussed and selective aspects of attention (Carswell, 1986).

Finally, the limited domain of the present analysis must be reitterated. We have focussed here upon geometric objects, with the quantitative attributes represented as different aspects of the geometry. Our analysis has therefore ignored other object properties such as color and brightness. Given the separable status of these dimensions from that of shape, it may well be that they produce a qualitatively different category of effects when their role in integration and independent tasks is examined. Such data, along with the further refinement of the information processing mechanisms underlying the compatibility of proximity hypothesis remain to be compiled.

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